

# **A LARGE-SCALE, END-TO-END PROCESS MODELING AND SIMULATION ENVIRONMENT FOR COMPOSITE MATERIALS MANUFACTURING AND TESTING**

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## **ABSTRACT**

Army systems and components are being designed and constructed to fulfill mission requirements for the Future Force and for Future Combat Systems (FCS). In many cases, these systems will utilize complex composite structures as core components. This paper discusses a modeling and simulation environment focused on composites acquisition from part design to testing. Also discussed is the computational environment that has been designed to quickly field these and related simulation codes.

## **1. INTRODUCTION**

Key to Army efforts dealing with FCS and the Future Force will be a mix of both manned and unmanned combat systems. The major goal for these systems is to have increased survivability, lethality, and operational ranges. Accordingly, a major push is underway to develop materiel systems that will support these requirements. The Army has focused on developing advanced composite materials for these systems due to their wide range of uses and advantageous properties.

However, a significant problem persists in the use of polymeric composite materials; the incremental nature of complex composite material developments and associated risks precludes streamlined acquisition and fielding. The time from original system design to completed product testing is too long and may be complicated by continual redesigns and changes to the manufacturing process to overcome unforeseen difficulties. The entire process needs to be integrated into a virtual framework to give system designers the ability to investigate and optimize the end-to-end process of composite acquisition from design to testing.

## **2. END-TO-END PROCESS SIMULATION**

A suite of advanced computing and simulation capabilities has been developed to provide the required functionality and address these end-to-end requirements.

These tools have been developed in close cooperation with the Research, Development and Engineering Centers (RDECs) and the Department of Defense (DOD) industrial base. The models consist of a combination of multi-disciplinary numerical analysis tools and a computational environment to allow these tools to take advantage of large-scale DOD parallel computing assets.

The current set of tools for end-to-end process simulation focuses on the resin transfer molding (RTM) manufacturing process. The RTM process is designed for large throughput, high-quality, net-shape production. The tools consist of a liquid composite molding simulation, a convection, conduction, and exothermic resin curing process model, and multi-scale residual thermal stress analysis.

### **2.1. Fluid Flow**

Initially, the RTM process is modeled as isothermal flow of resin through a fibrous preform. These simulations are done using the Composite Manufacturing Process Simulation Environment (COMPOSE) software. COMPOSE uses an implicit algorithm based on a pure finite element method [Mohan 1999]. Part designers and engineers can effectively utilize COMPOSE to predict and optimize resin infusion. Of primary interest is how long it will take to infuse a closed mold since this directly impacts the rate of manufacture and can be problematic for resin systems that gel quickly. Also of interest are the pressures created during manufacture and the rate of resin flow. These impact the mold tooling configurations and can predict areas where resin velocity might damage complex material lay-ups in the composite.

### **2.2. Heat Transfer and Resin Cure Kinetics**

While isothermal manufacturing simulations are adequate in many cases, many processes using high performance resin systems require the analysis of heat transfer and resin cure kinetics to fully understand the manufacturing process and identify the thermally induced residual stresses. An additional modeling and simulation capability, known as PhoenixFlow, has been developed to capture these effects. Since these values must be

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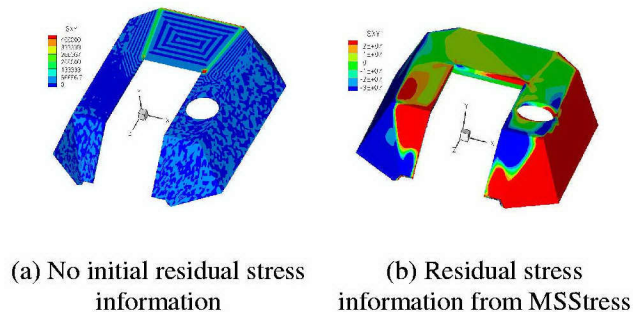
computed in tandem with the flow progression, PhoenixFlow has been tightly coupled with the process models in COMPOSE.

### 2.3. Multi-scale Residual Thermal Stress Analysis

The process thermal gradient output from PhoenixFlow is used in a final simulation step to predict the thermal residual stresses induced during the composite manufacturing process. These residual stresses typically form during the cool-down phase of manufacture after the resin has cured. The Multi-scale Residual Thermal Stress Analysis (MSSStress) software utilizes the temperature profiles of PhoenixFlow to compute these stresses.

## 3. VIRTUAL TESTING

With the recent addition of the MSSStress code, it is now possible to address end-to-end simulation requirements for manufacturing feasibility up to and including part testing in a virtual environment. A computational solid mechanics code (P-DINOSAURUS) was used to highlight the importance of incorporating residual stresses for dynamic loading analysis [Kanapady 2003]. Figure 1 shows a representative part where an initial blast loading was applied to the upper middle panel. Figure 1a shows the shear stress results after several time steps when no initial stress information has been incorporated in the simulation. In contrast, Figure 1b shows the same loading conditions with the initial process-induced stresses included in the computation. The obvious stress distribution differences could potentially influence the decisions made by part designers and would be vital to any service life behavior models.



**Figure 1. Impact of incorporating initial stress states for dynamic loading analysis.**

## 4. A COMPUTING ENVIRONMENT FOR PARALLEL FINITE ELEMENT ANALYSIS

The entire development and coupling process for these simulation codes has been greatly enhanced by the

use of the newly developed Simple, Parallel, Object-oriented Computing Environment for the Finite Element Method (SPOOCEFEM) [Henz 2004]. The framework provides an object-oriented code development tool for quick deployment of finite element-based software to run on both serial and parallel computers. The tedious task of managing and developing multi-threaded codes is left to the SPOOCEFEM toolkit. The hierarchical class structure allows for growth and maturation into an expanding class of finite element-based applications.

## CONCLUSION

The combination of COMPOSE, PhoenixFlow, and MSSStress provides a novel capability to completely model the RTM manufacturing process and predict residual stresses. The suite of tools allows for manufacturing optimization and streamlined acquisition. The capability to couple with computational structural mechanics codes bridges the gap between manufacturing and testing and hence provides process engineers with a powerful tool. The SPOOCEFEM modeling and simulation code development toolkit has greatly reduced the overall development time for these applications as well. It can easily be used to create new serial and parallel codes and couple applications to form multi-disciplinary computational environments.

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